SYSTEM, METHOD, AND MEDIUM FOR MONITORING PERFORMANCE OF AN ADVANCED PROCESS CONTROL SYSTEM

FIELD OF THE INVENTION

The present invention relates generally to the monitoring of advanced process control systems and more particularly to a system, method, and medium of monitoring the performance of a process output during semiconductor manufacture in relation to specification limits and monitoring the accuracy of a model that predicts the performance of the process output.

BACKGROUND OF THE RELATED ART

Semiconductor manufacture is becoming an increasingly automated process requiring precise methods of process control to ensure a quality output. Since the process is automated, safeguards are required to protect the manufacturing system and acknowledge when the manufacturing system, or tool, is unstable and is performing poorly.

Typically, there are only several factors that are measured during the semiconductor manufacturing process, for example, thickness of a film after the film has been deposited, polished, and/or etched. Because of this, occasionally there will be situations in which the tool

performance changes due to factors that are not directly measured. For example, one factor that is not directly monitored that can cause failures in a semiconductor device is an increased amount of particles on the wafer, where the increase in particles is caused by an increase in the pressure in a chamber where the manufacturing process is being performed. As the manufacturing process is designed, an experiment may be conducted to determine how many particles are introduced based on various levels of pressure. Since particles cannot be measured while the manufacturing process is executing, the designer must assume that the model is correct.

For situations in which there is no automated control, changes in the process performance as a result of errors in the model may be directly observed in the wafer properties. In the particles example, when the pressure in the chamber increases, the increase in the amount of particles on the wafer may be directly observed as a change in the thickness of the wafer. A human controller would notice the change in the wafer thickness and, in examining the process to determine the source of the thickness increase, would notice that the pressure had changed. The human controller would also perhaps notice that the change in pressure had caused the increase in the number of damaging particles on the wafer.

When advanced process control ("APC") techniques are applied, however, the APC methodology attempts to compensate for any changes in the manufacturing process and such changes may not be as easily observed. In the particles example, the thickness of the wafer is regulated, such that, when the model has predicted perfectly the required pressure in the chamber, as the pressure changes during execution of the process the thickness of the wafer does not change. However, when the model is not correctly predicting the behavior of the process, these pressure variations may cause an increase in particles to occur. However, although particles are being introduced and are damaging the wafer, the APC will not automatically detect these variations in pressure (*i.e.* the APC only detects an increase in the thickness of the wafer).

Thus, the use of advanced process control methods demonstrates a need for examining the behavior of the process in the context of a process that is being controlled. Two types of monitoring techniques, for example, process health monitoring and model health monitor, are often used to fulfill this need.

Process health monitoring may be used to effectively monitor, for example, an automated process that is under computer control. Process health monitoring detects deviation of controlled outputs of the process, or tool, away from some predetermined target area. Process health

monitoring may, itself, be an automated procedure. Process health monitoring methods provide high-level information for, for example, each controlled output of a process. For example, process health monitoring may be applied to chemical mechanical planarization ("CMP"), chemical vapor deposition ("CVD"), etching, electrochemical plating processes, ("ECP"), physical vapor deposition ("PVD"), etc. Such monitoring is accomplished by taking measurements of the process parameters that are of concern, then, to perform statistical analysis of those measurements, and, finally, to compare the statistical analysis to desired limits. Thus, a determination is made as to whether any specified controlled output(s) has strayed too far from a predetermined target.

Model health monitoring, which may be used to monitor each run-to-run ("R2R") control model for CMP, CVD, ECP, PVD, etc., detects deviation of, for example, the R2R model from the actual behavior of the process, or tool. Model health monitoring also may be an automated procedure. In the case of model health monitoring, the statistical analyses may include such pertinent information as model predictions and necessary previous data to perform these model predictions. Health monitoring may, itself, be an automated procedure.

Prior methods of process and model health monitoring employed indices relating to such monitoring. However, prior methods of monitoring were used for continuous

processes such as, for example, controller performance monitoring. Controller performance monitoring looks at a desired, best controller performance based on specific data, which are calculated using time series analysis, and takes a ratio of a current variance to the minimum variance controller performance. However, unlike with semiconductor manufacturing processes, controller performance monitoring takes into account only the continuous process, rather than monitoring distinct points in the process.

A continuous process, in general, refers to a process that is run in a mode where things are constantly coming in and constantly going out. A simple example is a tank that has fluid coming in and fluid going out. In a continuous process, the goal is to continually maintain the process in a certain state. For example, in the case of the tank, the goal would be to control the rate at which fluid is being pumped into, or out of, the tank such that the level of fluid in the tank is maintained at a constant level.

Controller performance monitoring is performed using minimum variance control theory for systems that have dynamics. In other words, the dynamic process is monitored only to determine what factors are affecting the maintenance of the continuous, on-going process. Prior methods of process and model health monitoring made use of the dynamic equations that are used to do control of such continuous processes.

In contrast, semiconductor processes are usually modeled as static processes for the purposes of run-to-run control. Rather than the manufacturing of a wafer being a continuous process, once a wafer is completed, the process is over. The process, itself, is repeated for subsequent wafers without being altered. A static, or discrete, process such as manufacturing a wafer can only be monitored in terms of how the process performed for prior, discrete manufacturing occurrences. An action in a static process (for example, a deposition time change or change in polish time), which occurred on the previous three wafers, may not have much of an effect on the processing of the subsequent wafer. Such static processes lack the dynamic equations used to model continuous process and, therefore, the model and process health monitoring techniques utilized for continuous process cannot be employed in monitoring static processes, *e.g.*, semiconductor manufacturing.

What is desired is a method and system that allows a controller to monitor the performance of a static manufacture process during the entire cycle of the process such as to maintain the performance of the process as the process is repeated.

SUMMARY OF THE INVENTION

The present invention addresses the lack in the prior art described above by providing techniques to monitor static processes and to quantize the results of the

monitoring with one or more indices. In the case of model health monitoring, the one or more indices can be used to monitor the performance of the process controller. In the case of process health monitoring, the one or more indices can be used to monitor the performance of the process, itself. An index, for example, a number, that characterizes the performance of either the controller or the process provides an "at-a-glance" metric that provides information as to whether or not the controller or the process is performing within acceptable limits. The purpose of the one or more indices is to provide some notification to, for example, a human operator that something in the on-going manufacturing process requires attention.

In general, embodiments of the present invention contemplate that model health monitoring for a static process, such as semiconductor manufacturing, estimates a variance of a specific controlled output over time and, then, benchmarks, or compares, this variance with an expected variance. Based upon this comparison of actual variance to the expected variance, an estimate is provided of how well the process is being controlled or how well the model is able to predict the behavior of the process and thus able to control the process. The result of this estimate is then calculated as a single, model health index. In one or more embodiments of the present invention, the model health index may also be used to trigger some sort of notification function if the controller and/or the model is

not operating within acceptable limits or seems in danger or doing operating outside of these acceptable limits.

In general, embodiments of the present invention contemplate that process health monitoring for a static process, such as semiconductor manufacturing, estimates not only the variance of a specific controlled output over time, but also a bias, the difference between the actual specific controlled output and a target output. The estimated bias and the estimated variance is then used to construct a probability distribution of how likely it is that the controlled output will be within some desired performance limits. Based upon this probability distribution, a single, process health index can be calculated that represents this likelihood. In other embodiments of the present invention, the process health index may also be used to trigger some sort of notification function if the process is not operating within acceptable limits or seems in danger or doing operating outside of these acceptable limits.

In monitoring static processes, such as semiconductor wafer manufacture, the model and/or process health index also gives an indication of the entire manufacturing process for a number of wafers by indicating whether an error in the manufacture of a particular wafer, for example, a wafer whose thickness is effected by a build up of particles, is due to an actual defect in the model and/or the process, for example, a change in the pressure of the manufacturing

chamber, or whether the error is an isolated, non-representative fluke, such as a bad wafer. The calculation of the model and/or process health index ideally provides a filtering mechanism by which isolated errors are not reflected in the index by determining whether a particular controlled output is non-representative outlier value.

It is one feature and advantage of the present invention to monitor the performance of a process model using one or more indices.

It is another feature and advantage of the present invention to monitor the performance of a process output using one or more indices.

It is another feature and advantage of the present invention to monitor the performance of multiple process models using one or more indices.

It is another feature and advantage of the present invention to monitor the performance of multiple process outputs using one or more indices.

These and other features and advantages of the present invention are achieved in a method for monitoring performance of an advanced process control system for at least one static process output. One or more embodiments of the present invention includes a method for monitoring performance of an advance process control system for at least one process output, which includes receiving process

performance data for the at least one static process output and comparing the process performance data to a predicted value for the process performance and/or a target value for the process performance. The method also includes calculating at least one index that reflects comparison of the process performance data to the predicted value and/or the target value for the process performance. The method further includes indicating the results of the calculation on the at least one index. Indicating the results includes sending an indication to a controller that the at least one index is beyond an acceptable point, halting processing of the at least one process output if the at least one index is beyond an acceptable point, and/or storing the at least one index as an indication of the processing performance of the at least one process output.

One or more embodiments of the present invention also includes a method for monitoring performance of an advanced process control system for at least one process output that includes receiving process performance data for the at least one process output and then calculating a model health index and/or a process health index. The model health index indicates an estimate of an ability of a model to predict the behavior of the at least one process output as compared to an expected output. The process health index indicates an estimated probability of violation by the at least one process output of predefined specification limits. The method also includes indicating the results of the

calculation based on the at least one of the model health index and the process health index.

One or more embodiments of the present invention also includes a method for monitoring performance of an advanced process control system for at least one process output that includes calculating a variance of a prediction error for a processing performance of the at least one process output and/or a probability for violating specification limits of the processing performance of the at least one process output. The variance and probability are based on an exponentially weighted moving average.

If the variance of the prediction error is calculated, the method also includes calculating a model health index. The model health index is a ratio of an exponentially weighted moving average-based estimate of a standard deviation of the prediction error to an expected estimate of the prediction error. The exponentially weighted moving average-based estimate of the standard deviation of the prediction error is derived from the variance of the prediction error.

If the probability for violating specification limits is calculated, the method further includes calculating a process health index. The process health index is a ratio of the probability for violating the specification limits to a specified probability limit. The method also includes

indicating the results of the calculation based on the model health index and/or the process health index.

One or more embodiments of the present invention also includes a method for monitoring performance of an advanced process control system for at least one process output that includes receiving process performance data for the at least one process output and calculating a current model health index or a current process health index. The current model health index indicates an estimate of an ability of a model to predict the behavior of a current one of the at least one process output as compared to an expected output. The current process health index indicates an estimated probability of violation by a current one of the at least one process output of predefined specification limits.

If the current model health index is calculated, the method also includes calculating a subsequent model health index, which indicates an estimate of an ability of a model to predict the behavior of a subsequent one of the at least one process output as compared to an expected output. If the subsequent model health index is calculated, the method further includes storing the current model health index and the subsequent model health index, such that comparing the current model health index and the subsequent model health index give an indication of a processing performance of the at least one process output.

If the current process health index is calculated, the method also includes calculating a subsequent process health index, which indicates an estimated probability of violation by a subsequent one of the at least one process output of predefined specification limits. If the subsequent process health index is calculated, the method further includes storing the current process health index and the subsequent process health index, such that comparing the current process health index and the current process health index gives an indication of the processing performance of the at least one process output.

One or more embodiments of the present invention also includes a method for monitoring performance of an advanced process control system for at least one process output that includes calculating a current variance of a prediction error for a processing performance of the at least one process output and/or a current probability for violating specification limits of the processing performance of the at least one process output. The current variance and the current probability are based on an exponentially weighted moving average.

If the current variance of the prediction error is calculated, the method also includes calculating a current model health index. The current model health index is a ratio of a current exponentially weighted moving average-based estimate of a standard deviation of the prediction

error to an expected estimate of the prediction error. The current exponentially weighted moving average-based estimate of the standard deviation of the prediction error is derived from the current variance of the prediction error.

If the current model health index is calculated, the method further includes calculating a subsequent model health index, which is calculated in a substantially similar manner to the current model health index. If the subsequent model health index is calculated, the method also includes storing the current model health index and the subsequent model health index, such that comparing the current model health index and the subsequent model health index gives an indication of the processing performance of the at least one process output.

If the current probability for violating specification limits is calculated, the method further includes calculating a current process health index. The current process health index is a ratio of the probability for violating the specification limits to a probability limit.

If the current process health index is calculated, the method also includes calculating a subsequent process health index, which is calculated in a substantially similar manner to the current process health index. If the subsequent process health index is calculated, the method further includes storing the current process health index and the subsequent process health index, such that comparing the

current process health index and the subsequent process health index give an indication of the processing performance of the at least one process output.

One or more embodiments of the present invention also includes a method for monitoring performance of an advanced process control system for a plurality of process outputs that includes calculating a first model health index of a process performance of a first one of the plurality of process outputs and/or a first process health index of the process performance of the first one of the plurality of process outputs. The method also includes calculating a second model health index of the process performance of a second one of the plurality of process outputs and/or a second process health index of the process performance of the second one of the plurality of process outputs.

If the first model health index and the second model health index are calculated, the method further includes calculating an aggregate model health index of the process performance of the plurality of process outputs. If the first process health index and the second process health index are calculated, the method also includes calculating an aggregate process health index of the process performance of the plurality of process outputs.

One or more embodiments of the present invention also includes a method for monitoring performance of an advanced process control system for at least one process output that

includes estimating a process deviation. The process deviation indicates deviation of a process performance from a target process performance and/or a model of the process performance. The method also includes characterizing a current estimate of the process performance using a first index that represents the deviation of the process performance from the target process performance and/or a second index that represents the deviation of the model performance from a specified model performance. The method further includes performing a notification function based on the value of the first index and/or the second index.

The features and advantages of the present invention are also achieved in a system for monitoring performance of an advanced process control system for at least one process output. The system includes a first memory that stores a predicted value for process performance of the at least one process output and/or a target value for process performance of the at least one process output. The system also includes a second memory that stores process performance data of the at least one process output and a third memory that stores at least one of a model health algorithm and a process health algorithm. The model health algorithm is used to calculate a model health index of the process performance and the process health algorithm is used to calculate a process health index of the process performance. The system further includes a processor that calculates the model health index using the model health algorithm and/or

the process health index using the process health algorithm. The model health index is calculated based on a comparison of the predicted value and the process performance data of the at least one process output. The process health index is calculated based on a comparison of the target value and the process performance data of the at least one process output.

One or more embodiments of the present invention also includes a system for monitoring performance of an advanced process control system for at least one process output that includes one or more tools, which measure the at least one process output. The system also includes a controller, coupled to tool(s), which provides for central control of the tool(s).

The controller implements instructions for controlling the tool(s), including: estimating a process deviation, which indicates deviation of a process performance from a target process performance and/or a model of the process performance; characterizing a current estimate of the process performance using a first index that represents the deviation of the process performance from the target process performance and/or a second index that represents the deviation of the model performance from a specified model performance; and performing a notification function based on the value of the first index and/or the second index.

The features and advantages of the present invention are also achieved in a computer-readable medium of instruction for monitoring performance of an advanced process control system for at least one static process output. The instruction includes, receiving process performance data for the at least one process output and comparing the process performance data a predicted value for the process performance and/or a target value for the process performance. The instruction also includes calculating at least one parameter that reflects comparison of the process performance data to the predicted value for the process performance and/or the target value for the process performance. The method also includes indicating the results of the calculation based on the at least one parameter.

One or more embodiments of the present invention also includes a computer-readable medium of instruction for monitoring performance of an advanced process control system for at least one static process output. The instruction includes, receiving process performance data for the at least one process output and calculating a model health index and/or a process health index. The model health index indicates an estimate of an ability of a model to predict the behavior of the at least one process output as compared to an expected output. The process health index indicates an estimated probability of violation by the at least one process output of predefined specification limits.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a block diagram illustrating a computerized process control system that may implement one or more embodiments of the present invention;

FIGURE 2 is a flow chart illustrating a method of calculating a model health index, according to one or more embodiments of the present invention;

FIGURE 3 is a flow diagram illustrating development of an example of initial model used in calculating the model health index;

FIGURE 4 is a schematic illustrating a relationship between input and output variables;

FIGURE 5 is a flow chart illustrating a method of calculating a process health index, according to one or more embodiments of the present invention;

FIGURE 6 is a graph illustrating a standard normal distribution of a probability for violating specification limits of a tool;

FIGURE 7 is a flow chart illustrating an example of the calculation of an aggregate model and/or process health index for three controlled outputs;

FIGURE 8 illustrates an example of a visual display that can be used to track the health of a system based on a health index;

FIGURE 9 illustrates an example of a visual display that can be used to track the health of a system over time based on a health index;

FIGURE 10 is a block diagram of a computer system that includes tool representation and access control for use in one or more embodiments of the present invention; and

FIGURE 11 is an illustration of a floppy disk that may store various portions of the software according to one or more embodiments of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

Reference now will be made in detail to various embodiments of the present invention. Such embodiments are provided by way of explanation of the invention and are not intended to be limited thereto. In fact, those of ordinary skill in the art may appreciate upon reading the present specification and viewing the present drawings that various modifications and variations can be made.

Monitoring the process and model health of the tool allows a controller, whether a human controller or some automated controller, to evaluate the performance of the tool. For example, alarms and warnings, which can be

triggered by a decrease in either the process or model health of the tool, can be configured such that the monitoring system can stop the tool, for example, if the process and/or model health goes beyond a certain limit. Alternatively, if the process and/or model health goes beyond, for example, some less severe limit, the controller may be notified by, for example, an e-mail, a page, or by a message send to a personal data assistant ("PDA").

FIGURE 1 is a block diagram illustrating an example of a computerized process control system, which may be used to implement one or more embodiments of the present invention. The system includes a control system, such as controller 102. Controller 102 may be any type of computer system capable of controlling a semiconductor manufacturing process. Controller 102 provides for central control of, and communication with, for example, one or more standard tools 106, which measure, for example, semiconductor wafers. Tools 106 are pieces of semiconductor manufacturing equipment that implement, for example, CMP, CVD, etching, and other such processes on a wafer.

I. Model Health Monitoring

FIGURE 2 is a flow chart illustrating a method of calculating the model health index in a semiconductor wafer manufacturing environment, according to one or more embodiments of the present invention. In general, the model

health index, I^M, is a time varying parameter and, in one or more embodiments of the present invention, is calculated based on the ratio of a current estimate of an exponentially weighted moving average ("EWMA") based estimate of the standard deviation of the prediction error, σ^{actual}, versus an expected estimate, σ^{ideal}, where σ^{ideal} is a given value. The better the model is at predicting the controlled outputs of the tool, the greater the value I^M will be. If the model is performing poorly, σ^{ideal} will be less than σ^{actual}, and I^M will be less than 1. If the model is performing well, then σ^{ideal} is greater than σ^{actual} and the ratio will be greater than 1. The value of I^M is, for example, limited between 0 and 1. Thus, I^M is calculated as follows:

$$I^M = \min\left\{1, \frac{\sigma^{ideal}}{\sigma^{actual}}\right\}.$$

A methodology for obtaining σ^{actual} is discussed below.

The length of the process history, which is involved in the calculation of the model health, is determined by a specific EWMA coefficient, λ, which is a given value (step 202). It should be noted that "given" values, as described herein, may be determined by experience or through direct measure, as generally known to those skilled in the art. A predicted value for the controlled output of the

semiconductor wafer is determined based on a process model (step 204), as described below in greater detail.

The calculation of the model health index is an iterative process that is performed by considering the difference between an actual value of a controlled output of, for example, a semiconductor wafer k+1, y_{k+1}^{actual}, and a predicted value for the controlled output of the semiconductor wafer k+1, $y_{k+1}^{predicted}$, where "k" indicates the wafer number (step 206). If this difference is larger than an estimate of the standard deviation of the prediction error for the previous wafer k, σ_k^{actual} (step 208), multiplied by a factor, *K*, indicating that the model is significantly different from the actual controlled output of the tool for that wafer, then that controlled output is ignored as a flier, or a non-representative outlier value, which is not representative of the controller output of the tool. The initial value of σ_k^{actual}, σ_0^{actual}, is given (step 202).

Since the process for determining the model health relies upon the most recently received information, more accurate values for σ_k^{actual} are "learned" by continuously gathering information from the process. Because the initial value of the standard deviation is assumed, the first several values of σ_k^{actual} will most probably not accurately reflect the actual standard deviation of the process, and

thus, the difference between y_{k+1}^{actual} and $y_{k+1}^{predicted}$ will almost always be greater than σ_k^{actual}. Therefore, screening for outliers, or flier, which involves a value, K, and the current estimate of the standard deviation of the prediction error, σ_k^{actual}, does not occur until the wafer number is greater than some specified wafer number, N_W (step 210). The initial estimation of the standard deviation of the prediction error, thus, always is used for the first several wafers, up to some wafer number N_w, which is a given value (step 202). The previous considerations can be summarized by the following conditional equation:

$$if\ \left|y_{k+1}^{actual} - y_{k+1}^{predicted}\right| \le K \cdot \sigma_k^{actual} \text{ OR } k+1 \le N_w, \qquad \text{(Equation 1)}$$

where K is a given coefficient (step 202).

If the condition holds true, an EWMA estimate of prediction error variance for the wafer k+1, D_{k+1}, is calculated (step 218). In general, D is an estimate of the predication error variance, or in other words, an estimate of the difference in an expected controlled output for a wafer and the actual controlled output for that wafer, that is calculated for a number of different wafers that undergo the process. D_{k+1} is based on the difference between y_{k+1}^{actual} and $y_{k+1}^{predicted}$, the length of the process history, and the estimate of the prediction error variance for the previous

wafer k, D_k. In one or more embodiments of the present invention, this can be calculated as follows:

$$D_{k+1} = \lambda(y_{k+1}^{actual} - y_{k+1}^{predicted})^2 + (1-\lambda)D_k \,, \qquad \text{(Equation 2)}$$

where D_0 is given (step 202). Of course, it should be understood that other specific ways to calculate D_{k+1} are also contemplated.

The estimate of the standard deviation of the prediction error for the wafer k+1, σ_{k+1}^{actual}, is then calculated (step 220) as follows:

$$\sigma_{k+1}^{actual} = \sqrt{D_{k+1}} \,. \qquad \text{(Equation 3)}$$

The model health index, I^M, for the wafer k+1, as contemplated by one or more embodiments of the present invention, can then be calculated (step 222) as described previously:

$$I^M{}_{k+1} = \min\left(1, \frac{\sigma^{ideal}}{\sigma_{k+1}^{actual}}\right). \qquad \text{(Equation 4)}$$

In the next iteration, wafer k+1 becomes wafer k (step 224) and the values D_{k+1} and σ_{k+1}^{actual} become D_k and σ_k^{actual}, respectively.

If the condition does not hold true (from Equation 1), the controlled output for wafer k+1, y_{k+1}^{actual}, is considered a non-representative outlier value, or a flier. Therefore, the values of D_{k+1} and σ_{k+1}^{actual} are not calculated (step 212) but are taken as the values of D_k and σ_k^{actual}, respectively. Thus, the model health index for wafer k+1, I_{k+1}^M, remains the same as the model health index for the previous wafer k, I_k^M (step 214). Wafer k+1 then becomes wafer k (step 216). It should be understood that other specific ways to calculate I^M are also contemplated by one or more embodiments of the present invention.

The complete dynamic calculation of I_{k+1}^M can be summarized as follows:

$$
\begin{aligned}
&\textit{if} \ \left|y_{k+1}^{actual} - y_{k+1}^{pred}\right| \le K \cdot \sigma_k^{actual} \quad \text{OR} \ k+1 \le N_w \\
&\quad D_{k+1} = \lambda(y_{k+1}^{actual} - y_{k+1}^{predicted})^2 + (1-\lambda)D_k \\
&\quad \sigma_{k+1}^{actual} = \sqrt{D_{k+1}} \\
&\textit{else} \\
&\quad D_{k+1} = D_k \\
&\quad \sigma_{k+1}^{actual} = \sqrt{D_{k+1}}
\end{aligned}
$$

FIGURE 3 is a flow diagram illustrating development of an initial model based upon knowledge of the tool. An initial understanding of the system is acquired in step 302, which is used to design and run a design of experiments (DOE) of step 304. The DOE desirably is designed to

establish the relationship between or among variables that have a strong and predictable impact on the processing output one wishes to control, e.g., film thickness or some other film property. The DOE provides data relating to process parameters and process outcome, which is then loaded to the advanced process control system in step 306. The advanced process control system may be a controller or computer that uses the data to create and update the model. The model can be represented as raw data that reflects the system, or it can be represented by equations, for example multiple input-multiple output linear, quadratic and general non-linear equations, which describe the relationship among the variables of the system. Process requirements such as output targets and process specification are determined by the user in step 308, which are combined with the DOE data to generate a working model in step 310.

In developing the model, for example for a sub-atmospheric chemical deposition ("SACVD") process, film properties of interest 412 are identified and outcome determinative processing model variables 414 are selected for the model, as illustrated schematically in FIGURE 4. The specific film properties of interest may vary depending upon the type of film deposited, and thus the film properties of interest 412 and processing model variables 414 of FIGURE 4 are shown by way of example.

Regardless of the type of film substance for which a model is created, to obtain DOE data, an experiment is run which perturbs or varies the values of the processing variables of interest about a center point (or median value). One or more processing variables can be varied. The film properties of interest in the resultant film are measured for each combination of inputs. Data can be acquired empirically, by carrying out a series of experiments over a range of values of the processing variables. The data is fit to the appropriate curve (linear or non-linear) to define the model.

II. Process Health Monitoring

FIGURE 5 is a flow chart illustrating an example method of calculating the process health index in a semiconductor wafer manufacturing environment, according to one or more embodiments of the present invention. In general, the process health index, I_{k+1}^{P}, is a time varying parameter and, in one or more embodiments of the present invention, is calculated based on the ratio of a current estimate of the probability for violating specification limits, $\Pr_{k+1}^{calc}$, versus a probability limit, $\Pr^{limit}$, where $\Pr^{limit}$ is a given value, for example, 95%. If the tool is performing beyond the predetermined specification limits, indicating that the process is performing poorly, $\Pr_{k+1}^{calc}$ will be greater than

$\Pr^{limit}$. If, however, the tool is performing within the predetermined specification limits, indicating that the process is performing within acceptable limits, $\Pr_{k+1}^{calc}$ will be less than $\Pr^{limit}$. The value of I_{k+1}^{P} is, for example, limited between 0 and 1, with a higher value indicating acceptable performance of the process. Thus, I_{k+1}^{P} is calculated as follows:

$$I_{k+1}^{P} = \max\left(0, 1 - \frac{\Pr_{k+1}^{calc}}{\Pr^{limit}}\right).$$

A methodology for obtaining $\Pr_{k+1}^{calc}$ is discussed below.

The length of the process history, which is involved in the calculation of the process health, is determined by a specific EWMA coefficient, λ, which is a given value (step 502). As stated previously, it should be noted that "given" values, as described herein, may be determined by experience or through direct measure, as generally known to those skilled in the art. A set of specification limits for the controlled output of the processed semiconductor wafer is determined based on a desired performance of the tool (step 504).

The probability that a controlled output of the tool will be within with certain specification limits can be modeled using a standard normal distribution bell curve, as

illustrated in FIGURE 6. Regions I and III represent a probability beyond $\Pr^{limit}$, for example, a probability greater than 95% that the controlled output will be beyond the specification limits, and is thus an undesirable controlled output. Region II represents a probability that is within the specification limits. The relationship of I^P for a wafer k+1 to this standard probability distribution can be illustrated mathematically as follows:

$$I_{k+1}^{P} = \begin{cases} \Pr_{k+1} \geq \Pr^{limit} : 0 \\ \Pr_{k+1} < \Pr^{limit} : 1 - \left(\frac{\Pr_{k+1}}{\Pr^{limit}} \right) \end{cases}, \qquad \text{(Equation 5)}$$

where $\Pr_{k+1}$ is a value for $\Pr^{calc}$ for a wafer k+1.

Referring back to FIGURE 5, the calculation of the process health index is an iterative process that is performed by considering the difference between an actual value of a controlled output of, for example, a semiconductor wafer k+1, y_{k+1}^{actual}, and target value for the controlled output of the semiconductor wafer k+1, y_{k+1}^{target}, where "k" indicates the wafer number (step 506):

$$\Delta_{k+1} = y_{k+1}^{\text{actual}} - y_{k+1}^{\text{target}}. \qquad \text{(Equation 6)}$$

If this difference is larger than an estimate of the standard deviation of a target deviation for the previous wafer k, σ_k^{actual}, multiplied by a factor K (step 508),

indicating that the actual controlled output of the tool for that wafer is significantly different from target controlled output, then that controlled output is ignored as a flier, or a non-representative outlier value, which is not representative of the controlled output of the tool. The initial value of σ_k^{actual}, σ_0^{actual}, is given (step 502).

As described previously, more accurate values for σ_k^{actual} are "learned" by continuously gathering information from the process. Since the initial value of the standard deviation is assumed, the first several values of σ_k^{actual} will most probably not accurately reflect the actual standard deviation of the process, and thus, the difference between y_{k+1}^{actual} and y_{k+1}^{target} will always be greater than σ_k^{actual}. Therefore, screening for outliers, or fliers, which involves a value, K, and the current estimate of the standard deviation of the target deviation, σ_k^{actual}, does not occur until the wafer number, N_W, is greater than some specified wafer number (step 510). The initial estimation of the standard deviation, thus, always is used for the first several wafers, up to some wafer number N_W, which is a given value (step 502). The previous considerations can be summarized by the following conditional equation:

$$if\ \left|\Delta_{k+1}\right| \leq K \cdot \sigma_k^{actual} \text{ OR } k+1 \leq N_W, \qquad \text{(Equation 7)}$$

where K is a given coefficient (step 502).

If the condition holds true, an EWMA estimate of target deviation variance for the wafer k+1, D_{k+1}, is calculated (step 512). In this case, D is an estimate of target deviation variance, or in other words, an estimate of the difference in a target controlled output for a wafer and the actual controlled output for that wafer that is calculated for a number of different wafers that undergo the process. D_{k+1} is based on the difference between y_{k+1}^{actual} and y_{k+1}^{target}, the length of the process history, and the estimate of the target deviation variance for the previous wafer k, D_{k+1}. In one or more embodiments of the present invention, this can be calculated as follows:

$$D_{k+1} = \lambda(\Delta_{k+1})^2 + (1-\lambda)D_k, \qquad \text{(Equation 8)}$$

where D_0 is given (step 502). Of course, it should be understood that other specific way to calculate D_{k+1} are also contemplated.

The estimate of the standard deviation of the target deviation for the wafer k+1, σ_{k+1}, is then calculated (step 514) as follows:

$$\sigma_{k+1} = \sqrt{D_{k+1}}. \qquad \text{(Equation 9)}$$

Next, an EWMA estimate of the target deviation mean for wafer k+1, M_{k+1}, is calculated (step 516) in one or more embodiments of the present invention as follows:

$$M_{k+1} = \lambda\Delta_{k+1} + (1-\lambda)M_k, \qquad \text{(Equation 10)}$$

where M_0 is given (step 502).

Finally, $\Pr_{k+1}^{calc}$, for wafer k+1 is calculated (step 518). In general, $\Pr^{calc}$ represents an estimate of the probability that a controlled output for a wafer will violate some predetermined, desired specification performance limits and is calculated for a number of different wafers that undergo the process. In one or more embodiments of the present invention, this is calculated as follows:

$$\Pr_{k+1}^{calc} = \Pr_k^{calc}\{USL < N(M_{k+1}, D_{k+1}) < LSL\}, \qquad \text{(Equation 11)}$$

where $\Pr_0^{calc}$ is given (step 502), such that $\Pr_{k+1}^{calc}$ is based upon the estimated probability for violating specification limits for wafer k, $\Pr_k^{calc}$, a predetermined upper specification limit ("USL"), a predetermined lower specification limit ("LSL"), and a normally distributed variable with the previously described "bell-curve" distribution (FIGURE 6). The actual, mathematical calculation of $\Pr_k^{calc}$ for a wafer k, which can be extrapolated for the calculation of $\Pr_{k+1}^{calc}$ as appropriate, is as follows:

$$\begin{aligned}\Pr_k^{calc} &= \Pr\{USL < N(M_k, D_k) < LSL\} \\ &= \Pr\{N(M_k, D_k) < LSL\} - \Pr\{N(M_k, D_k) < USL\}\end{aligned} \qquad \text{(Equation 12)}$$

with

$$\Pr\{N(M_k, D_k) < x\} = \frac{1}{2} erfc\left(x - \frac{M_k}{\sqrt{2D_k}} \right) \qquad \text{(Equation 13)}$$

and

$$erfc(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} e^{-t^2} dt \quad , \qquad \text{(Equation 14)}$$

where "x" represents either USL or LSL, as appropriate, and "erfc" is a complementary error function. Of course, it should be understood that other specific way to calculate $\Pr_{k+1}^{calc}$ are also contemplated.

The process health index, I_{k+1}^P, for the wafer k+1, as contemplated by one or more embodiments of the present invention, can then be calculated (step 520) as described previously:

$$I_{k+1}^P = \begin{cases} \Pr_{k+1} \geq \Pr^{limit} : 0 \\ \Pr_{k+1} < \Pr^{limit} : 1 - \left(\dfrac{\Pr_{k+1}^{calc}}{\Pr^{limit}} \right) \end{cases}.$$

In the next iteration, wafer k+1 becomes wafer k (step 522) and the values D_{k+1}, σ_{k+1}, and M_{k+1}, and $\Pr_{k+1}^{calc}$ become D_k, σ_k, M_k, and $\Pr_k^{calc}$, respectively.

If the condition does not hold true (from Equation 7), the controlled output for wafer k+1, y_{k+1}^{actual}, is considered a non-representative outlier value, or a flier. Therefore, the values of D_{k+1}, σ_{k+1}, and M_{k+1}, and $\Pr_{k+1}^{calc}$ are not calculated (step 524) but are taken as the values of D_k, σ_k, M_k, and $\Pr_k^{calc}$, respectively. Thus, the process health index for wafer k+1, I_{k+1}^P, remains the same as the process health index for the previous wafer k, I_k^P (step 526). Wafer k+1 then becomes wafer k (step 528). It should be understood that other specific ways to calculate I^P are also contemplated by one or more embodiments of the present invention.

The complete dynamic calculation of I_{k+1}^P can be summarized as follows:

$$\Delta_{k+1} = \left(y_{k+1}^{actual} - y_{k+1}^{target}\right)$$

$$\begin{aligned}
&\textit{if } \left|\Delta_{k+1}\right| \le K\sigma_k^{actual} \text{ OR } k+1 \le N_W \\
&\quad D_{k+1} = \lambda(\Delta_{k+1})^2 + (1-\lambda)D_k \\
&\quad \sigma_{k+1} = \sqrt{D_{k+1}} \\
&\quad M_{k+1} = \lambda(\Delta_{k+1}) + (1-\lambda)M_k \\
&\quad \Pr_{k+1}^{calc} = \Pr\{USL < N(M_{k+1}, D_{k+1}) < LSL\} \quad . \\
&\textit{else} \\
&\quad D_{k+1} = D_k \\
&\quad M_{k+1} = M_k \\
&\quad \Pr_{k+1}^{calc} = \Pr_k^{calc}
\end{aligned}$$

In general, both process and model health monitoring can be used to gain insight into the health of a process, although they provide different levels of analysis. As stated previously, the process health index provides an indication of how well the actual process is performing while the model health index provides an indication of whether or not the configuration of the process controller should be modified. Therefore, performing model health monitoring in addition to process health monitoring provides further information, which allows for increased refining and improvement of the control of the process.

III. Higher Level Health Monitoring

An advanced process control system may have multiple controlled outputs and also may have multiple process descriptors, which indicate different layers of a semiconductor product, as well as different products. For example, a particular tool may have multiple chambers, or resources, which are essentially places to process. On a single wafer, parameters that are typically controlled include, for example: average thickness, thickness uniformity, and dopant concentration. Although each controlled output or process descriptor can be monitored with a separate model and/or process health index, it may be more efficient to create a single, aggregate model health index and/or a single, aggregate process health index that characterizes either the health for a specific process

descriptor for a specific chamber or processing station, the health of the entire processing system for a specific process descriptor, or the health of the entire system for all process descriptors.

The higher-level health-monitoring, or aggregate, index for model health and/or process health is calculated, according to one or more embodiments of the present invention, using a mean of the indices. One type of mean is a geometric mean, calculated as follows:

$$I^{M,P}\Big|_{system} = \sqrt[N]{\prod_{i=1}^{N} I^{M,P}\Big|_{y_i}}\ , \qquad \text{(Equation 15)}$$

where N is the total number of controlled outputs being monitored in the system and y_i indicates a particular controlled output. Other, alternate methods of calculating the aggregate index may be used. It should be noted that a single, aggregate index can be calculated to monitor either the process health of the multiple outputs or the model health of the multiple output but not both the process health and model health.

FIGURE 7 is a flow chart illustrating an example of the calculation of an aggregate model and/or process health index for N controlled outputs. The model and/or process health index is calculated for a first controlled output, $I^{M,P}\Big|_{y_1}$ (step 710). The model and/or process health index is

then calculated for a second controlled output, $I^{M,P}\big|_{y_2}$ (step 720). These calculations continue until the model and/or process health index is calculated for an nth controlled output, $I^{M,P}\big|_{y_n}$ (step 730). The aggregate model and/or process health index, $I^{M,P}\big|_{system}$, is then calculated as described above (step 740).

IV. Health Tracking and Notification

FIGURE 8 illustrates an example of a visual display that can be used to track the health of a system based on a health index. In this example, display 800 illustrates a graphical display of model health indices for seven controlled outputs 802, 804, 808, 808, 810, 812, and 814. Display 800 shows that the model used to predict the actual values of the controlled outputs is performing well, as indicated by the model health index values being close to or equal to 1.

Display 850 illustrates a graphical display of model health indices for seven controlled outputs 852, 854, 857, 858, 860, 862, and 864. By contrast with display 800, in this example, display 850 shows that the models used to predict the actual values of the controlled outputs is performing poorly, as indicated by the low model health index values.

FIGURE 9 illustrates an example of a visual display, display 900, which can be used to track the health of a system over time based on a health index. In this example, the health of a process over time is represented by line graph 910. The value of the process health index is shown on vertical axis 920 and the time progression is shown on horizontal axis 930. The decreasing value of the process health index indicates that the controlled output being tracked is degrading, continuing to veer further and further away from the target output value.

The model and/or process health index can be used to perform several notification functions of the health of the tool or system. For example, if the model and/or process health index drops below some predetermined threshold, *e.g.*, below .4, a notification message may be sent to a human controller using, for example, an e-mail, a page, or a wireless PDA. Other notification methods are, of course, possible. Likewise, notification can be sent to a computerized controller, where the computerized controller may respond by raising some warning flag. If the model and/or process health index drops below some critical point, the human or computerized controller may respond by shutting down the system, and thus halting processing of the tool until the cause of the health degradation can be located and remedied.

The model and/or process health index may also be used to generally track the overall health of the system. The various iterative values of the model and/or process health index may be stored in some memory either as a single instance of health (FIGURE 8), or over time (FIGURE 9), and then displayed or otherwise delivered to the human or computerized controller.

V. Computer Implementation

Various aspects of the present invention that can be controlled by a computer can be (and/or be controlled by) any number of control/computer entities, including the one shown in FIGURE 10. Referring to FIGURE 10 a bus 1002 serves as the main information highway interconnecting the other components of system 1000. CPU 1004 is the central processing unit of the system, performing calculations and logic operations required to execute the processes of embodiments of the present invention as well as other programs.

Read only memory (ROM) 1020 and random access memory (RAM) 1018 constitute the main memory of the system. As contemplated by the present invention, a number of parameters, including, for example, the actual data from the controlled output, the model data indicating a predicted value for the controlled output as used to calculated the model health index, the specification data indicating a target value for the controlled output, and the actual model

and/or process health indices as they are calculated, may be stored in the main memory of the system. Therefore, any number of ROM 1020 and/or RAM 1018 may be included in the system to accommodate storage of these parameters. Additionally, the instructions for calculating the model and/or process health indices may also be stored in these main memories.

Disk controller 1022 interfaces one or more disk drives to the system bus 1002. These disk drives are, for example, floppy disk drives 1026, or CD ROM or DVD (digital video disks) drives 1024, or internal or external hard drives 1028. These various disk drives and disk controllers are optional devices.

A display interface 1014 interfaces display 1012 and permits information from the bus 1002 to be displayed on display 1012. Display 1012 can be used in displaying a graphical user interface. Communications with external devices such as the other components of the system described above can occur utilizing, for example, communication port 1016. Optical fibers and/or electrical cables and/or conductors and/or optical communication (e.g., infrared, and the like) and/or wireless communication (e.g., radio frequency (RF), and the like) can be used as the transport medium between the external devices and communication port 1016. Peripheral interface 1010 interfaces the keyboard 1006 and mouse 1008, permitting input data to be transmitted

to bus 1002. In addition to these components, system 1000 also optionally includes an infrared transmitter and/or infrared receiver. Infrared transmitters are optionally utilized when the computer system is used in conjunction with one or more of the processing components/stations that transmits/receives data via infrared signal transmission. Instead of utilizing an infrared transmitter or infrared receiver, the computer system may also optionally use a low power radio transmitter 1032 and/or a low power radio receiver 1030. The low power radio transmitter transmits the signal for reception by components of the production process, and receives signals from the components via the low power radio receiver. The low power radio transmitter and/or receiver are standard devices in industry.

Although system 1000 in FIGURE 10 is illustrated having a single processor, a single hard disk drive and a single local memory, system 1000 is optionally suitably equipped with any multitude or combination of processors or storage devices. For example, system 1000 may be replaced by, or combined with, any suitable processing system operative in accordance with the principles of embodiments of the present invention, including sophisticated calculators, and hand-held, laptop/notebook, mini, mainframe and super computers, as well as processing system network combinations of the same.

FIGURE 11 is an illustration of an exemplary computer readable memory medium 1100 utilizable for storing computer readable code or instructions. As one example, medium 1100 may be used with disk drives illustrated in FIGURE 10. Typically, memory media such as floppy disks, or a CD ROM, or a digital videodisk will contain, for example, a multi-byte locale for a single byte language and the program information for controlling the above system to enable the computer to perform the functions described herein. Alternatively, ROM 1020 and/or RAM 1018 illustrated in FIGURE 10 can also be used to store the program information that is used to instruct the central processing unit CPU 1004 to perform the operations associated with the instant processes. Other examples of suitable computer readable media for storing information include magnetic, electronic, or optical (including holographic) storage, some combination thereof, etc. In addition, at least some embodiments of the present invention contemplate that the medium can be in the form of a transmission (e.g., digital or propagated signals).

In general, it should be emphasized that various components of embodiments of the present invention can be implemented in hardware, software or a combination thereof. In such embodiments, the various components and steps are implemented in hardware and/or software to perform the functions of the present invention. Any presently available or future developed computer software language and/or

hardware components can be employed in such embodiments of the present invention. For example, at least some of the functionality mentioned above could be implemented using C, C++, visual basic, Java, or any assembly language appropriate in view of the processor(s) being used. It could also be written in an interpretive environment such as Java and transported to multiple destinations to various users.

The many features and advantages of the invention are apparent from the detailed specification, and thus, it is intended by the appended claims to cover all such features and advantages of the invention, which fall within the true spirit and scope of the invention. Further, since numerous modifications and variations will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction illustrated and described, and accordingly, all suitable modifications and equivalence may be resorted to, falling within the scope of the invention.

It is to be understood that the invention is not limited in its application to the details of construction and to the arrangements of the components set forth in the following description or illustrated in the drawings. The invention is capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed

herein are for the purpose of description and should not be regarded as limiting.